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Microcalorimeter observations of L-shell spectra of Ne- through Fe-like Au ions in an EBIT

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Abstract.

L-shell x-ray emission of Au has been observed of the plasma that flows from reduced-size hohlraums under high-power laser irradiation. In order to provide tools for determining the temperature, charge state distribution and mean charge of such a plasma, we have measured the L-shell emission from highly charged gold ions in the SuperEBIT electron beam ion trap under bombardment by electrons at energies from 10 to 18 keV. The emission was recorded with an x-ray microcalorimeter, featuring an instrumental line width of 10 eV in the region of primary interest. Lines from ironlike Au^{53+} through neonlike Au^{69+} ions were identified. We find that the strong $3d_{5/2} => 2p_{3/2}$ emission features are well separated for at least the highest 13 charge states and can be used to diagnose the charge state distribution.

1. Introduction

In the original concept of inertial confinement fusion (ICF) experiments, laser light was supposed to depose energy into the outer shell of a fuel pellet which then would undergo compression by shock waves. To improve symmetry, an intermediate stage has been added in which the pellet is placed inside a gold-coated cylindrical hohlraum of centimeter size. Many beams of laser light enter the hohlraum through the openings at the ends of the cylinder and strike the inner wall. A plasma is generated that produces x rays; these x rays provide a more uniform energy flux than the original lasers that then heats the fuel pellet. Experiments of this type are going on at various laboratories.

It would be interesting to find out how to deposit the available laser energy in the smallest possible space enclosed by walls of high-Z material. For this purpose, reduced-size (half a millimeter) hohlraums with only one opening have been constructed. In these 'hot' hohlraums, the plasma can fill the volume during the laser pulse, and then spills out. In fact, the effluent plasma interacts with the incoming laser light and limits further access to the hohlraum [1, 2]. In order to learn about this interaction, it is necessary to characterize the effluent plasma by density, temperature, charge state distribution, and mean charge of the high-Z material.

In gold plasmas with temperatures of tens of keV, the dominant charge state is likely to be neonlike Au^{69+}. The $3d_{5/2} \rightarrow 2p_{3/2}$ transitions of Ne-like ions and the neighboring ions of lower charge have been seen to form a well-spaced "picket-fence" pattern [3, 4], similar to observations on M-shell transitions of gold and tungsten [5, 6, 7]. The shape of this pattern depends on the abundance of the ions of each charge state and thus on the ionization balance which, in turn, depends on the electron temperature. This radiation pattern, therefore, can serve as a means for determining both the average ionization state of the plasma and its electron temperature.

2. Experiment

We have recorded the $3d_{5/2} \rightarrow 2p_{3/2}$ emission pattern of highly charged gold ions in an electron beam ion trap under well controlled laboratory conditions. The adjustable beam energy of the device allows us to step through the charge states, enabling unambiguous identification of the strong L-shell lines and line blends, in this experiment of Au^{53+} through Au^{69+} (Fe- through Ne-like ions), as well as the determination of charge state distributions.

The experiment was performed at the SuperEBIT electron beam ion trap [8] at the Lawrence Livermore National Laboratory. The device has been optimized for spectroscopic studies of highly charged ions [9], including the study of spectra needed for diagnosing high energy density plasmas [10]. About every two seconds, a laser injection system supplied Au to the ion trap, where it was quickly ionized by the electron beam. Every 19 s the content of the trap was dumped to halt the accumulation of possible contaminants, such as barium and tungsten, and then the trap cycle was repeated. X-ray emission from the ions in the trap was detected by means of a cryogenic microcalorimeter built by Goddard Space Flight Center [11]; out of the array of 32 small HgTe absorbers ("pixels"), 12 were read out at the same time. In order to record x rays with energies as high as 18 keV, the microcalorimeter was operated at a (slightly elevated) temperature of T=65 mK. The individual pixel pulse height was calibrated against n=1-2 lines of He- and H-like ions of Ar, Ni, and Ge, and then all pixel spectra were summed. For single x-ray transitions at 8 to 10 keV, a line width (FWHM) of about 10 eV was found, which corresponds to a resolving power of about 900. Spectral features measured with larger line widths (15 to 18 eV) reveal the presence of line blends. The quantum efficiency of the HgTe absorbers in the detector varies significantly over the range of the present observations. Corrections for filter and Be window transmission and for detection efficiency have been applied.

The experiment primarily aimed to measure the 2-3 transitions of Au emitted in the x-ray energy range from 9 to 12 keV. The highest charge state of interest was Au^{69+} (Ne-like); the ionization potential (IP) of 18 keV of this ion was chosen as the highest electron beam energy used in the measurements. The ionization potentials of the next lower charge state ions are 8.4 keV and consecutively lower. However, the IP refers to the valence electron (n=3 for those ions below the Ne-like ion), whereas the x-ray transitions of present interest relate to inner-shell excitation.

Figure 1 shows sections of emission spectra obtained at electron beam energies from 10 to 18 keV. Evidently the Au emission varies with the electron beam energy: as E_{beam} decreases, the intensity of major emission features shifts to lower energies. The picket-fence structure of the $3d_{5/2} \rightarrow 2p_{3/2}$ emission features in our spectra extends to ironlike Au^{53+}, with a picket-fence spacing of about 40 eV. The highest-energy peak of each line group belongs to the Ne-like ion. Line blending becomes significant for charge states below about vanadiumlike Au^{56+}, and for those ions full modeling is needed to predict the emission. However, in higher-temperature plasmas, where the average ion charge $\langle Z \rangle$ is well above 56+, the $3d_{5/2} \rightarrow 2p_{3/2}$ features provide a reasonably good indication of the charge balance even in the absence of detailed modeling.

3. Atomic structure and collisional-radiative calculations

We have used the Flexible Atomic Code (FAC) of Gu [12] to generate fine-structure atomic levels and rate data for Au ions from H-like (Au^{78+}) to Zn-like (Au^{49+}). The atomic structure and rate data were then used in the collisional-radiative and spectral synthesis code SCRAM [13] to calculate level populations, charge state distributions, and emission spectra. At the low densities of the electron-beam ion trap, where electronic state populations are overwhelmingly concentrated in ground state configurations and line emission tends to be limited by direct collisional excitation and ionization, a set of "coronal" configurations is deemed adequate to describe the major transitions with reasonable accuracy.

At higher densities, multi-step processes lead to significant population in multiply excited configurations, opening up new channels for population transfer and giving rise to strong satellite emission features. In order to cope with that complexity (in a reasonable approximation), we use a hybrid atomic structure scheme in which the fine-structure "coronal" configurations are supplemented with relativistic configuration averaged levels (nlj terms), taking single and double excitations, CI corrections and more into account. This hybrid atomic structure approach [13] with CI correction preserves much of the accuracy of fine structure modeling and permits us to model complex electronic systems with reasonable completeness. For calculations of $\langle Z \rangle$, we further supplement the hybrid model with screened hydrogenic superconfigurations up to $n = 10$ employing the simplest approximation options described in [14]. $\langle Z \rangle$ calculations by the hybrid model and FLYCHK [14] indicate that the emission patterns observed from electron beams of 10 to 18 keV (see Figure 1) can be associated with a Maxwellian T_e of 5 to 15 keV. The first dozen charge states below the Ne-like ion can be associated with individual peaks in our spectra, but the complexity increases with the number of electrons. Most of the lower charge states contribute to several peaks at a time.

At temperatures above 10 keV or densities below about 10^{19}cm^{-3}, our calculations are fairly insensitive to n_e. At lower temperatures and at densities near or above 10^{12}cm^{-3}, the calculated mean charge state $\langle Z \rangle$ is sensitive to n_e due to increasing populations of multiply excited configurations. With increasing densities, the major transition features are broadened and can be shifted to lower energies by as much as 10 eV as the populations of multiply excited states with weakly bound spectator electrons increase. This is way beyond the density range in EBIT. However, the density effect is clearly present in some beam-foil spectra [16] which could not be interpreted properly at the time: The beam-foil x-ray lines associated with Ne-like ions are in good agreement with atomic structure calculations, but those of Na- and Mg-like ions are shifted to lower energies, because they depend on satellite line contributions excited at solid state density in the exciter foil.

4. Acknowledgements
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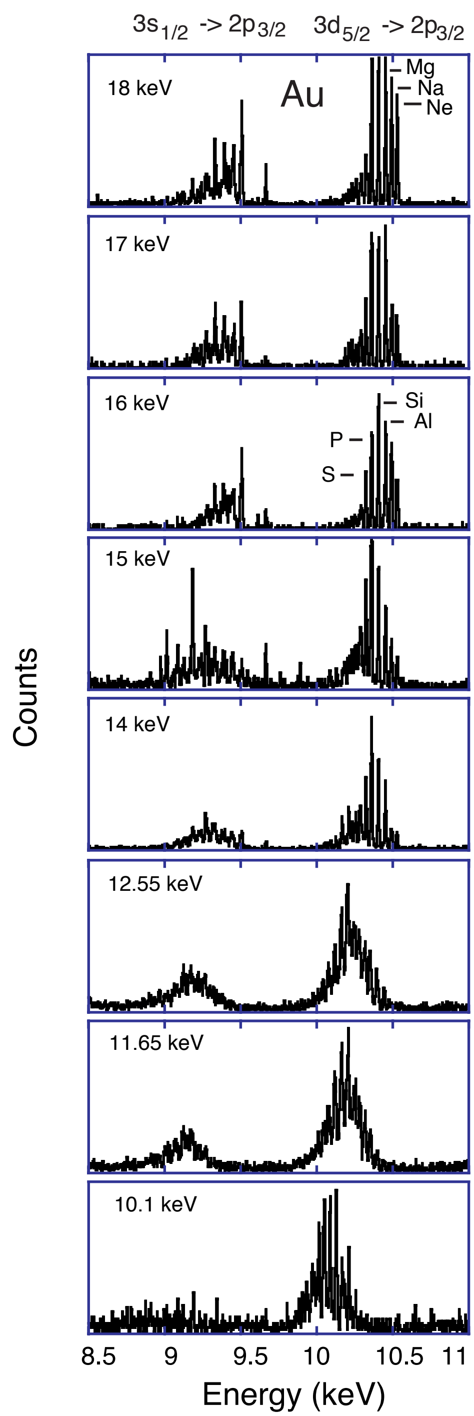

Figure 1. Range of the $n = 2 - 3$ emission of Au ions at eight electron beam energies. The microcalorimeter covered a spectral range from 0.5 to 18 keV. The transition arrays are identified on top. The picket-fence pattern of the lines from Ne- through S-like ions appears most clearly above 13 keV electron beam energy.

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